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THE EFFECT OF BASALT FIBER PRODUCTION TECHNOLOGY ON MECHANICAL PROPERTIES OF FIBER

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The effect of basalt fiber production technology on the mechanical properties of fiber (strength, electricity modulus, and ultimate deformation) is considered depending on the geometrical parameters of monofilaments.

The service properties and stability of products made of basalt fiber are determined not only by the chemical composition of the initial material, but also by filament production technology [1]. The studies were performed on basalt monofilaments produced in gas furnaces from melts: roving 9.5 – 10.5 μm in diameter produced by the continuous (spinneret) method; filaments up to 13 μm in diameter produced by the spinneret method with subsequent air blowing at normal temperature (duplex process); filaments 3.8 – 15 μm in diameter obtained from the melt produced in high-frequency induction electric furnaces (1.76 MHz) with subsequent air blowing at normal and elevated (300 – 400°C) temperatures.

To study the specific mechanical properties of the filaments produced by the continuous methods, three types of weakly twisted fiber (roving) were tested. The isolation of monofilaments from roving and subsequent measurement of the diameter of their cross section was carried out in accordance with GOST 6943.2–79, and stretching tests were carried out in accordance with GOST 6943.5–79. The results are shown in Fig. 1 and in Table 1.

The tested fibers had homogeneous color distribution along the whole filament, which is an indirect evidence of a relatively homogeneous chemical composition along the fiber length. The statistical distribution parameters of their elastic-strength and deformation characteristics are within the same limits, as in carbon monofilaments which have an obviously homogeneous chemical composition and are produced by the continuous method [2].

For the purposes of comparison, carbon fibers UKN-5000 with a round cross section selected from three lots, one reel from each lot, were tested as well (Table 2). The analysis of the obtained results indicated that such statistical parameters of the stability of material properties as the variation coeffi-

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TABLE 1

Determined fiber parameter	Fiber type, production method					
	roving			duplex process	blowing	
	RBN(b)-13–1200	RB-10–1000	RBK-600		hot air	air at normal temperature
Number of monofilaments	20	20	25	23	9	26
Mean value of filament diameter d, μm	10.1	10.5	9.5	12.2	6.3	14.8
Variation coefficient V_d of values d_i, %	9.1	13.5	19.2	37.7	47.6	48.0
Mean value of strength σ, MPa	2880.0	1760.0	3470.0	731.8	840.3	656.3
Variation coefficient V_σ of values σ_i, %	44.5	29.5	25.6	102.0	40.4	90.9
Mean value of elasticity modulus E, GPa	91.9	87.5	86.1	66.8	71.9	34.6
Variation coefficient V_E of values E_i, %	7.0	9.5	12.7	120.3	27.3	93.4
Mean value of ultimate deformation ε, %	3.29	2.13	4.36	1.12	1.17	1.90
Variation coefficient V_ε of values ε, %	44.2	32.7	24.3	26.8	29.8	29.5

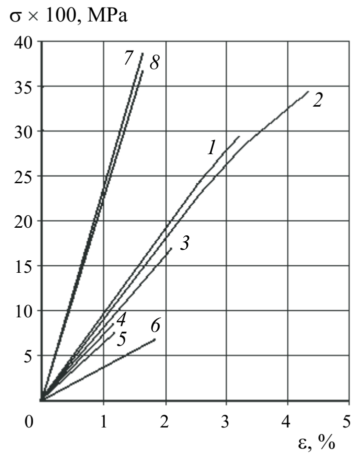

Fig. 1. Diagrams of carbon and basalt filament stretching: *1*) RBN(b)-13–1200; *2*) RB-10–1000; *3*) RBK-600; *4*) hot air blowing; *5*) spinneret method; *6*) air blowing at normal temperature; *7* and *8*) UKN-5000.

cients of cross-sectional diameter and elasticity modulus have virtually equal, relatively low values for the considered roving and carbon fibers.

Thus, the continuous method for basalt roving production is characterized by consecutive, rather lengthy stages of melting and vitrification, degassing and homogenization, and melt chilling [3], which ensures the stability of the geometrical sizes of the fiber cross section and the elasticity modulus, i.e., the elastic constant of fibrous material.

The presence of volume defects, such as inter-fiber cracks and cavities, specifics of their distribution in the longitudinal and radial directions, as well as the presence of surface defects (microcracks, indents, swellings) does not have a significant effect on altering the elasticity modulus of fiber, but produces a substantial decrease in the fiber strength. Depending on the specifics of distribution of volume and surface defects, the fiber strength can vary significantly, whereas the elasticity modulus remains virtually constant. Thus, the strength variation coefficients of the investigated carbon fiber UKN-5000 vary within the limits of 22.1 – 26.6%, basalt roving within 25.6 – 44.5%, whereas the elasticity modulus variation coefficients are within the limits of 9.5 – 14.0 and 7.0 – 12.7%, respectively.

Discrete basalt filaments produced by the duplex process and by using high-frequency induction furnaces with air

TABLE 2

Lot (reel) number*	d, μm	V_d, %	σ, MPa	V_σ, %	E, GPa	V_E, %	ε, %	V_ε, %
1	6.9	9.0	3779.8	26.6	218.8	11.0	1.72	25.5
2	6.9	8.1	3816.1	22.1	226.7	14.0	1.68	22.5
3	6.7	7.2	3929.9	26.2	226.0	9.5	1.72	23.8

* 30 filaments from each reel were isolated and tested.

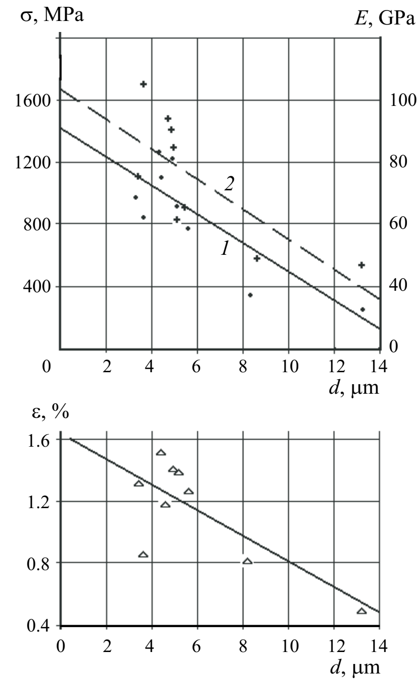

Fig. 2. Correlation dependences of ultimate strength σ (●), elasticity modulus E (+), and ultimate deformation ε (△) on cross-section diameter d of basal filament produced by air blowing at normal temperature: *1*) dependence of ultimate strength; *2*) dependence of elasticity modulus.

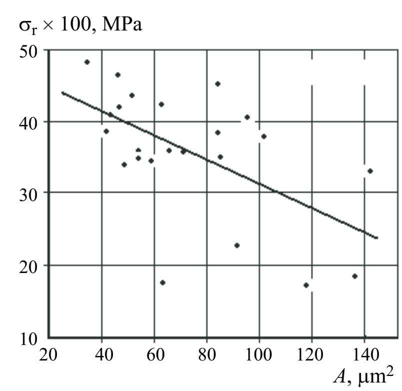

Fig. 3. Dependence of ultimate strength σ_r of basalt filament RBK-600 on the surface area of cross section A.

blowing under normal and increased temperatures differ significantly in all their parameters from the filaments produced continuously (Table 1). Their strength is 2.1 – 5.3 times lower than the strength of roving, and the elasticity modulus is lower by the factor of 1.2 – 2.7. At the same time, one should note the clear dependence of the strength, the elasticity modulus, and the ultimate deformation of discrete filaments on their diameter (Fig. 2). As the diameter decreases, the ultimate strength, the elasticity modulus, and the ultimate deformation increase. This relationship is less evident in basalt roving (Fig. 3).

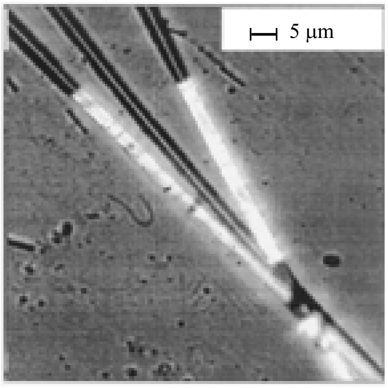

Fig. 4. Electron photo of superfine basalt monofilament produced without spinneret (in high-frequency furnaces) by air blowing at normal temperature.

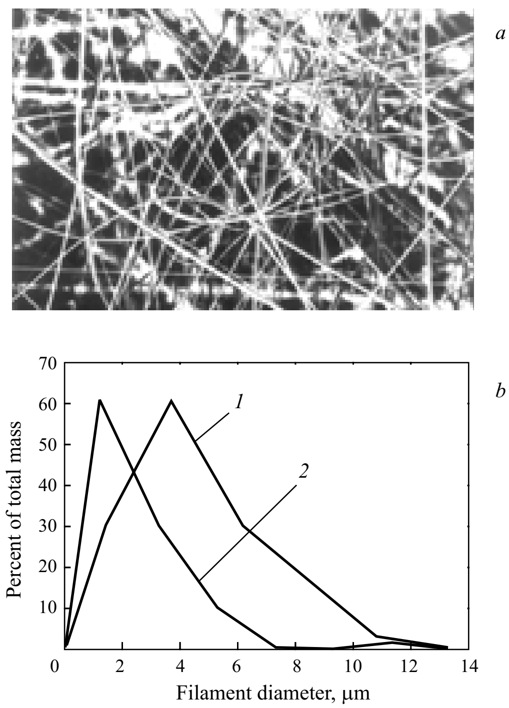

Fig. 5. General view of the macrostructure of basalt wool consisting of superfine filaments (*a*) and diagram of size distribution of monofilaments (*b*): *1*) duplex process; *2*) high-frequency furnace.

This fact is probably determined by the radial structure alteration across the filament section [4] upon the formation of a surface layer, which arises due to the phase heterogeneity of the melt when being cooled in the course of filament formation and mainly consists of crystalline forms which have the least surface energy; moreover the layer thickness virtually does not depend on the monofilament diameter. Therefore, its effect on the physicomechanical parameters of fiber is the most noticeable for small filament diameters (below 5 μm).

Another distinctive feature of the considered discrete fibers is the substantial instability of their cross-sectional diameter and physicomechanical properties. The variation of the values of the cross-section diameter is 37.7 – 48.0%. The substantial instability of cross-section sizes in monofilaments is determined by the differences in their deformation (thinning) properties, which presumably arise due to the inhomogeneous chemical composition and structure of the initial basalt melt and are manifested in color variations along the monofilament length (Fig. 4). Apparently, the time allocated by the technological regulations for melting basalt mixture and equalizing its chemical composition through thermal diffusion and for stabilizing the process of vitrification and homogenization is not sufficient, in contrast to the filament produced by the continuous method.

In fact, basalt wool is formed from an enormous multitude of monofilaments (Fig. 5), each of which (or a group of monofilaments) represents a different variety of basalt fibrous material, which has its own chemical composition and distribution specifics over the fiber volume and its own set of physicomechanical and thermophysical properties.

A difference in chemical composition inevitably produces a difference in the deformation and strength properties of discrete filaments and in their elasticity parameters, i.e., their modulus of elasticity. In this case, a significant spread is observed in mechanical parameters.

Thus, the strength variation in the filaments produced by the duplex process is 102.0%, the elasticity modulus variation is 120.3% (Table 1), and in the filaments produced by cold air blowing, the variation is 90.9 and 93.4%, respectively.

The use of hot air for blowing significantly reduces the spread in the elastic-strength parameters of basalt fiber: it drops to 40.4% in strength parameters, and an especially significant drop to 27.3% is seen in the elasticity modulus. At the same time, no decrease occurred in the spread in the filament diameter values and elongation deformation values (Table 1), which is possibly accounted for by a smaller diameter of the considered filaments.

The use of cold air in blowing not only causes a substantial spread in the elastic-strength parameters, but also lowers the average values of these parameters: the strength becomes 1.3 times lower, and the elasticity modulus is lowered 2.1 times. In the first case, one can only talk of a tendency to decrease, whereas in the second case, a significant decrease is observed.

The test for the significance of differences was carried out using the Fisher and Student criteria [5]. Using the Fisher criteria $F = S_1^2/S_2^2$ with the significance level $q = 0.05$ and the number of degrees of freedom of strength dispersion in the numerator $f_1 = n_1 - 1 = 25$ and in the denominator $f_2 = n_2 - 1 = 8$ ($S_{\sigma_1} = 596.3$ MPa, $S_{\sigma_2} = 339.5$ MPa), it was demonstrated that dispersions S_1^2 and S_2^2 are homogeneous, since $F_{\text{est}} = 3.09 < F_{\text{table}} = 3.18$. In this case the estimated

Student criterion value is smaller than the table value ($t_{est} = 0.87 < t_{table} = 2.03$), and therefore, the mean strength values $\sigma_1 = 840.3$ and $\sigma_2 = 656.3$ MPa are homogeneous as well and, consequently, their difference is not significant.

The elasticity modulus dispersions S_1^2 and S_2^2 are homogenous as well ($F_{est} = 2.72 < F_{table} = 3.18$), but in this case $t_{est} = 3.24 > t_{table} = 2.03$, and therefore, the mean values of elasticity moduli $E_1 = 71.9$ and $E_2 = 34.6$ GPa differ significantly.

When analyzing the correlation dependences between the mechanical characteristics and the filament diameter shown in Tables 3 and 4, one more distinction was established between the continuous fiber (roving) and the discrete fibers. It was established that an evident linear dependence exists in the considered continuous carbon and basalt fibers only between strength σ and ultimate deformation ε. The minimum value of the correlation coefficient for carbon fiber is equal to $r(\sigma, \varepsilon) = 0.78$, and for basalt roving 0.89. With the linear deformation, brittle destruction (Fig. 1), and low fluctuations of the elasticity modulus values this can mean that σ and ε depend on the same structural parameters and defects.

For the considered discrete fibers, a uniquely linear dependence was established between strength and elasticity modulus, regardless of the production method: the correlation coefficient $r(\sigma, E) = 0.76 – 0.98$ (Table 3). Such a clear relationship between the strength and the elastic properties in this case is presumably determined by the modification of the chemical and structural composition of the monofilaments, both specified parameters inevitably varying.

In spite of the fact that the considered carbon fiber was produced according to standard technology and has good elastic-strength properties, it differs from other carbon fibers of the same type in the scale dependence of mechanical properties on the cross-section diameter [6, 7].

Thus, by means of extending the duration of basalt melting, in order to fully complete the processes of vitrification, degassing, and homogenization, it is possible not only to diminish the spread in the elastic-strength properties of discrete filaments, but also to raise their average level to the level of strength properties in continuous filaments. The use of hot air in blowing probably decreases the internal residual stresses and stabilizes the structure of fibers, which can contribute to increasing their strength and decreasing the spread in their physicomechanical properties. In this case it is possible to increase the elasticity modulus of a discrete filament to the level typical of continuous basalt fibers (90 GPa), since the obtained preliminary results demonstrated that the existent differences in elastic properties of discrete and continuous fibers are slight and statistically insignificant.

TABLE 3

Parameters	Fiber type, production method					
	roving			duplex process	blowing	
	RBN(b)-13–1200	RB-10–1000	RBK-600		hot air	air at normal temperature
σ, E	+ 0.48	+ 0.27	+ 0.32	+ 0.98	+ 0.76	+ 0.94
σ, ε	+ 0.99	+ 0.93	+ 0.89	– 0.07	– 0.85	+ 0.16
E, ε	+ 0.35	– 0.08	– 0.08	– 0.24	+ 0.33	– 0.14
σ, d	– 0.50	– 0.08	– 0.43	– 0.47	– 0.82	– 0.59
E, d	– 0.53	– 0.43	+ 0.09	– 0.45	– 0.75	– 0.40
ε, d	– 0.46	+ 0.10	– 0.44	– 0.08	– 0.63	– 0.37

TABLE 4

Parameters of carbon fiber UKN-5000	Lot (reel) number		
	1	2	3
σ, E	+ 0.52	+ 0.31	+ 0.40
σ, ε	+ 0.93	+ 0.78	+ 0.93
E, ε	+ 0.20	– 0.33	+ 0.05
σ, d	– 0.08	– 0.44	– 0.46
E, d	– 0.44	– 0.50	– 0.38
ε, d	+ 0.08	– 0.14	– 0.31

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